AN ANALYSIS OF ROUTINE 300-MB. TRANSOSONDE FLIGHTS FROM JAPAN[1]

J. K. ANGELL

U. S. Weather Bureau, Washington, D. C.

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ABSTRACT

Routine Navy-sponsored 300-mb. transosonde flights from Japan for the months September 1957–February 1958 are analyzed. Statistics on the wind velocity, acceleration, and power spectra for the flights are indicated. With the aid of radiosonde data, the mean vertical motions and mean horizontal divergences along the flights are evaluated. Comparisons of transosonde velocities with geostrophic velocities obtained from National Weather Analysis Center maps are presented.

1. INTRODUCTION

Under the auspices of the United States Navy, routine 300-mb. transosonde flights, or constant level balloon flights, were initiated from Iwakuni, Japan, in the summer of 1957. Details concerning the transosonde system may be found in papers by Mastenbrook [1] and Mastenbrook and Anderson [2]. On these routine flights the balloons were positioned at 2-hourly intervals by Navy radio-direction-finding stations while the balloons were west of 135° W. longitude and by Federal Communications Commission radio-direction-finding stations while the balloons were east of this longitude. The positions so determined were placed on the meteorological teletypewriter circuits in Pearl Harbor and Norfolk for transmission to analysis centers and constituted the basic data from which 300-mb. wind velocities were estimated on a routine basis. More accurate and complete position data, however, were available from Navy and FCC logs made up in Pearl Harbor and Washington, D. C. The information presented in this paper is based solely upon data obtained from these logs.

2. TRAJECTORIES

Figure 1 shows, for the months of September through February, the trajectories of the flights which were tracked for at least one day. All the flights were at 300 mb. with the exception of a few 150-mb. flights in February which are shown in the figure by dashed trajectories. At the end points of the trajectories are given the flight numbers and, in parentheses, the flight durations in hours. Flight durations as long as 7 days were realized until the middle of November when the balloons began to fly over Europe. Owing to the restriction against flying over Eurasia, it then became necessary to limit all flight durations to 5 days, as noted in the transosonde flights for December, January, and February. The average speed along several of the flights that approached close to Europe exceeded 100 knots. For example, in November, flight 44 reached Ireland only 4 days after release from Japan, having traveled a distance exceeding 10,000 nautical miles.

Figure 2 gives mean 300-mb. transosonde trajectories for each of the five months September through January, and two mean trajectories for the month of February, one for the balloon flights at 300 mb. and one for the balloon flights at 150 mb. In order to keep some "memory" of the short-duration flights in the mean trajectories and to reduce the irregularity in mean trajectories resulting from the loss of flights of short duration, these short flights were extrapolated to 5 days by assuming that the mean daily changes in latitude and longitude of the flights remaining aloft represented an approximation to the changes in latitude and longitude which the flights of short duration would have experienced had they remained aloft. The mean monthly trajectories were then obtained by averaging the latitude and longitude positions of the actual and extrapolated trajectories at daily intervals following release.

In figure 2, the notation D_3 in the vicinity of Oregon indicates the average position of the December flights 3 days after release. For the months of November through February the mean monthly positions 3 days after release were over the western United States, even for the February flights at 150 mb. as indicated by the circled F_3 near El Paso. From the distances and directions between the daily mean positions, mean velocities were computed, as shown by the conventional wind barbs giving the average wind speeds in knots. For the first day following release from Japan, these wind speeds averaged about 110 knots during the winter months at 300 mb. and at 150 mb. in February. With the exception of the January trajectories, the mean transosonde trajectories traversed the west coast of North America farther to the north as midwinter was reached. Thus in the mean the October flights passed through Baja California, the November flights through California, the December flights through Oregon, and the February 300-mb. flights near the U.S.-Canadian border.

[1] The research reported in this paper was supported by the Office of Naval Research.

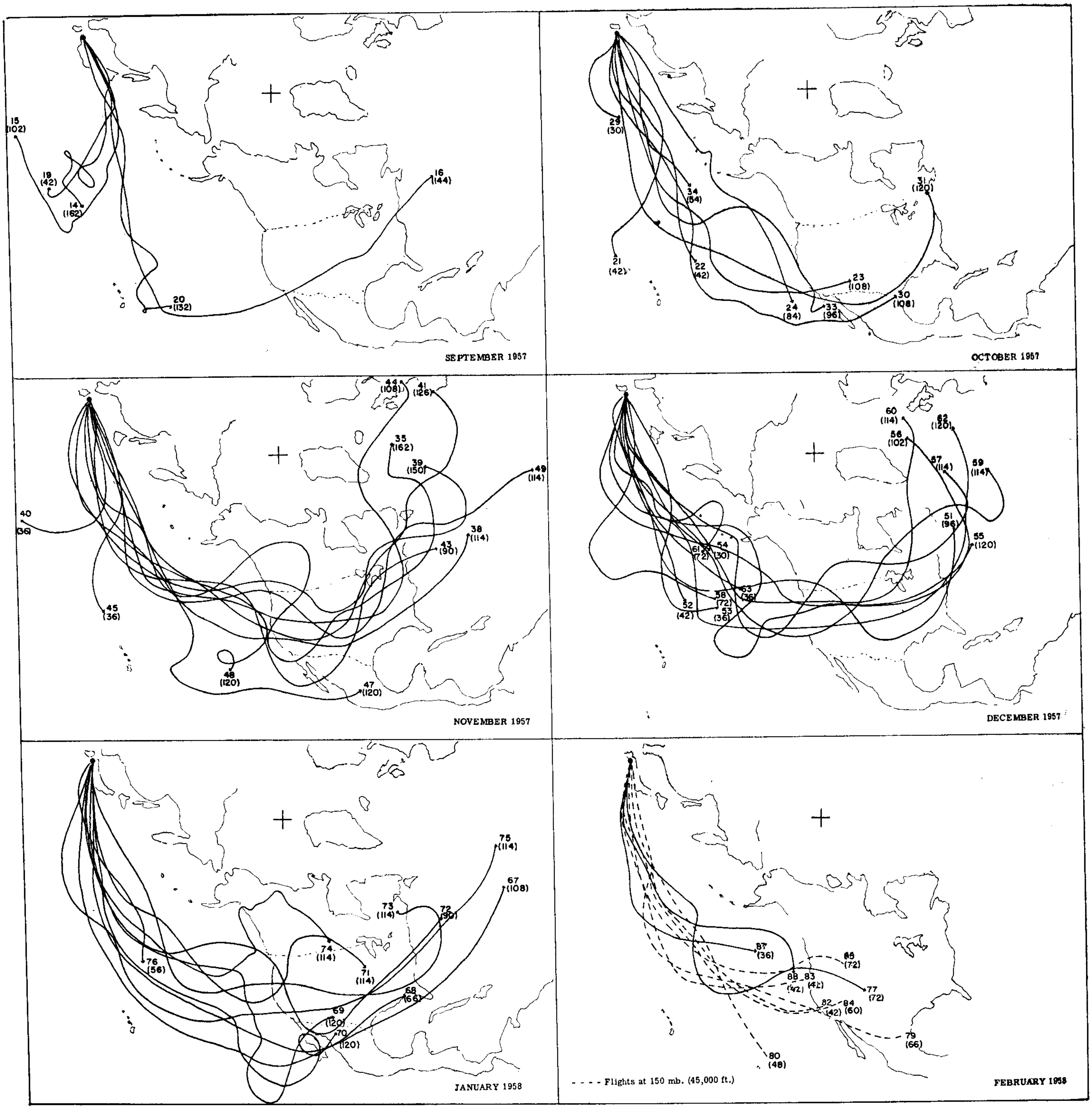

FIGURE 1.—Transosonde trajectories at 300 mb. (solid lines) and 150 mb. (dashed lines) for the months September 1957–February 1958 with the flight number and flight duration in hours (in parentheses) indicated at the end of each trajectory.

Figure 3 shows the mean trajectory for all flights during the 6-month period, determined in the manner indicated above. For all the flights the mean balloon position after 1 day was near the 180th meridian, after 3 days near the west coast of the United States, and after 5 days near the east coast of the United States. This mean trajectory remained very close to latitude 36° N. throughout, traversing the Pacific in a region where conventional upper-air data are lacking, as shown by the dots which represent the radiosonde stations in the Pacific area. The winds derived from the distances between daily positions along this mean trajectory indicate that in the mean for all 6 months the balloons moved eastward at an average speed of about 95 knots during the first day after release from Japan, whereas over the eastern Pacific and the United States the eastward movement averaged about half this value.

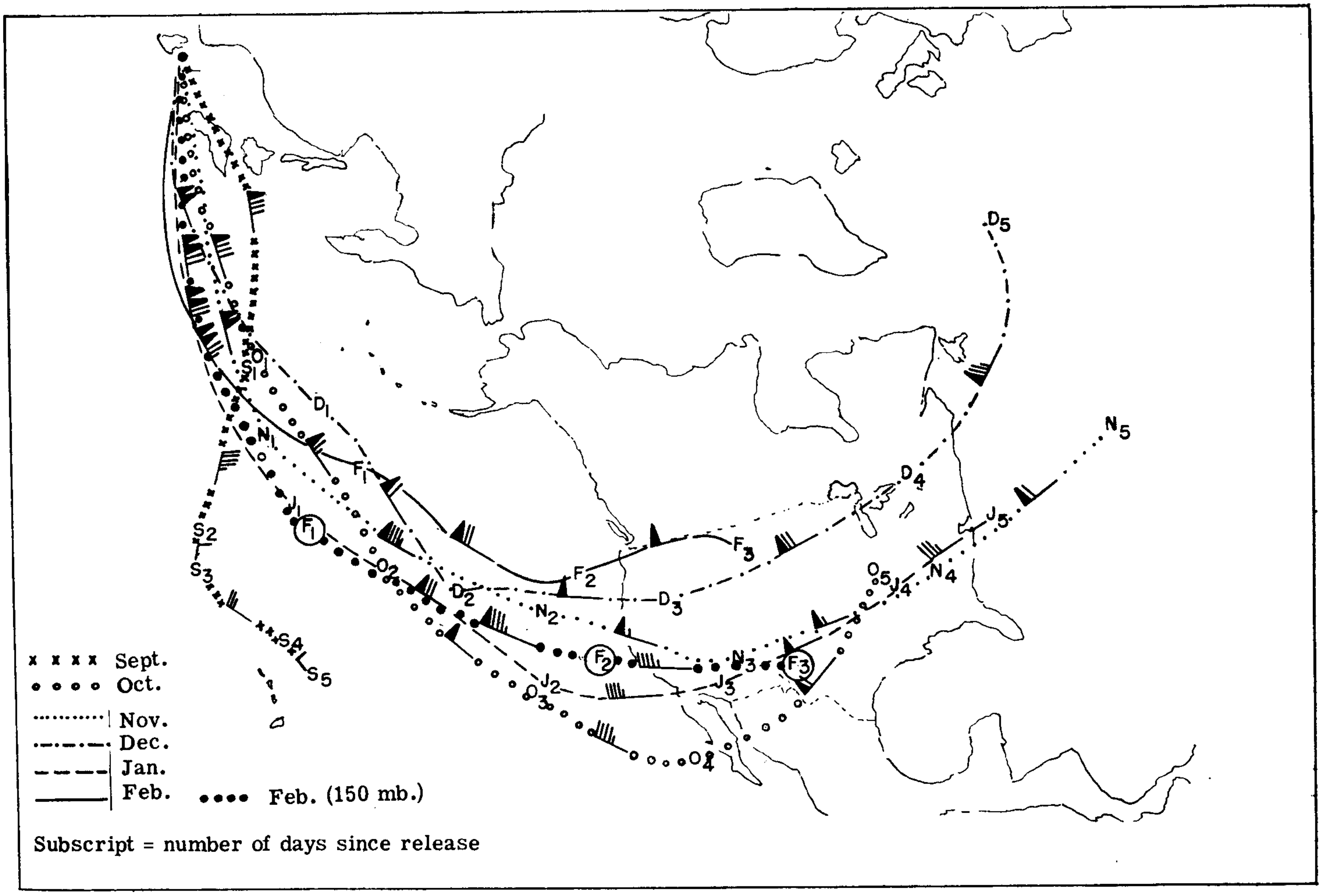

FIGURE 2.—Mean monthly transosonde trajectories for September 1957–February 1958 with the letters along the trajectories indicating the mean monthly transosonde positions at daily intervals following release (S=Sept., etc.); the numerical subscripts, the number of days since release; and the customary wind shaft and barbs, the derived 24-hour average velocities.

The ellipses centered on the daily positions along the mean trajectory represent the mean of the monthly standard deviations of position at daily intervals, obtained by finding the standard deviations of latitude and longitude positions. It is difficult to obtain reliable values for these mean monthly standard deviations of position owing to the tendency for the tracking networks to lose contact with balloons which go far south or far north—the very flights which would yield a large meridional standard deviation of position. Since the short duration trajectories had been extrapolated to 5 days by the technique described above, it seemed logical to obtain estimates of the standard deviations of position from the combination of actual and extrapolated trajectories. In the lower left-hand corner of figure 3 are given, in the left-hand sigma column, the mean standard deviations of the meridional positions, in degrees latitude, after a certain number of days, and in the right-hand column the mean standard deviations of the longitudinal positions, in degrees latitude, after a certain number of days. It may be noted that the longitudinal standard deviation increases nearly linearly with time, whereas the meridional standard deviation actually decreases slightly after 3 days. This implies that for these flights the balloons tended to be more widely dispersed latitudinally over the west coast of North America than over the east coast of North America. However, because of the difficulty in obtaining reliable standard deviations of position from flights of varying duration, this result may not be conclusive.

3. STATISTICS ON VELOCITY AND ACCELERATION

Owing to the difficulty of obtaining accurate balloon positions over the Pacific, some smoothing was necessary to obtain reliable velocities from the transosonde data. The smoothing involved averaging three latitude and longitude positions, each 2 hours apart, and replacement of the latitude and longitude position at the middle time by the average value. This was done so as to yield an averaged position every 6 hours, as shown in figure 4 by the dots. The numbers along the trajectory in this figure give the number of days since balloon release. The 6-hour average velocity was then determined from the distance and direction between the averaged 6-hourly positions. The acceleration was determined from changes in velocities 12 hours apart.

Tables 1 and 2 give some statistics on the 6-hour

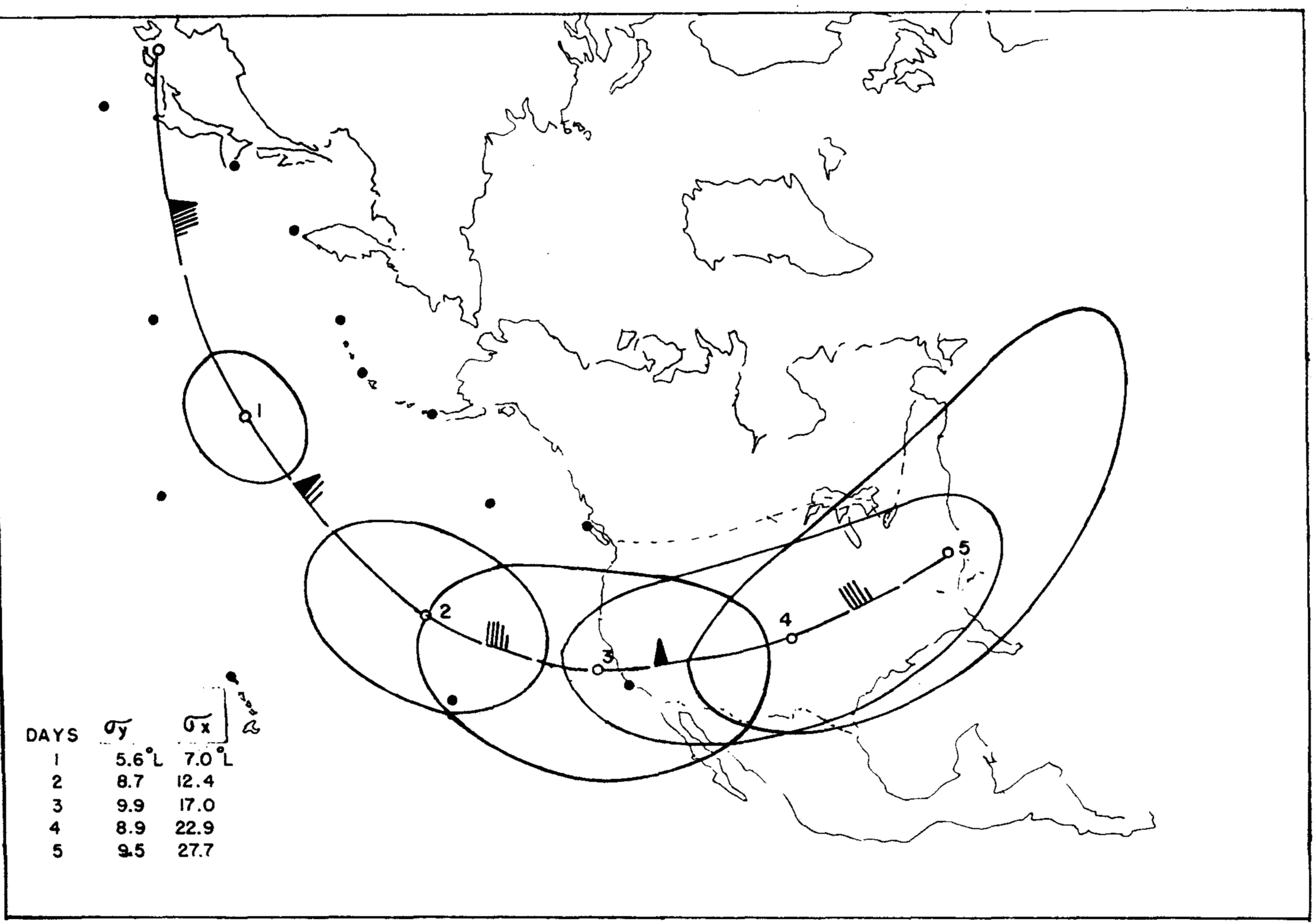

FIGURE 3.—Mean transosonde trajectory, September 1957–February 1958, with the numbers along the trajectory indicating the mean transosonde position at daily intervals following release; the wind symbols, the derived 24-hour average velocities; the ellipses, the mean-monthly standard deviations of position; and the dots, the adjacent upper-air stations in the Pacific.

average velocity and 12-hour average acceleration obtained in this way. It is seen that in this quadrant during November, December, and February, more than one-third of the winds at 300-mb. exceeded 100 knots, and that in February at 150 mb. about half the winds exceeded this value. It also may be noted that the average value

TABLE 1.—*Monthly statistics of 6-hour average 300-mb. wind velocities obtained from transosonde flights for September 1957 to February 1958*

Month 1957–58	Percentage of cases in which wind speed exceeded the given value (kt.)						Average wind speed (kt.)	Average product of zonal-meridional velocity components (kt.²)	Corr. coeff. between zonal-meridional velocity components	Cases
	25	50	75	100	125	150				
Sept.	72	47	22	9	1	1	47	33	0.03	97
Oct.	97	72	46	19	4	1	67	98	.10	113
Nov.	96	80	59	35	12	3	81	443	.28	197
Dec.	97	91	65	39	9	4	87	595	.22	161
Jan.	95	78	53	32	15	7	80	−53	−.04	168
Feb.	100	96	72	40	28	12	107	358	.21	25
Mean	93	77	53	30	10	4	77	258	.14	761
Feb. (150 mb.)	98	87	78	51	29	5	98	113	.15	55

for the products of the velocity components is 258 knots², a value close to that obtained by integrating around the hemisphere using synoptic data. The average correlation between the velocity components is +0.14, with only the month of January yielding a negative correlation.

In table 2 it is seen that for all months the tangential acceleration was less than the normal acceleration, in the average about 60 percent of the normal acceleration. It may also be noted that there was no strong correlation between tangential and normal acceleration, in other words, there was no obvious tendency for wind speeds to increase, say, in the troughs rather than on the crests of the trajectories. However, the positive correlation of 0.08 between tangential acceleration and meridional flow, suggests that the speed and kinetic energy of the balloons and air parcels tended to increase as they passed through the pretrough southerlies.

4. VERTICAL MOTION AND DIVERGENCE ALONG TRAJECTORIES

The constant level balloon is constrained to remain near a surface of constant height or pressure and thus gives no direct information on the vertical air motion. As shown by Neiburger and Angell [3], an indirect indication of the vertical motion may be obtained by the adiabatic method if the temperature and lapse rate along the balloon trajectory are known. At present, to estimate the vertical motions, it is necessary to extrapolate to the position of the balloon the 300-mb. temperatures and lapse rates obtained from radiosonde data. In figure 5B we show, as a function of longitude, the average elevations of those air parcels which initially were associated with the constant level balloons at 30,000 feet. These mean elevations were derived from vertical motions obtained from temperature differences along the individual trajectories as estimated from 12-hourly National Weather Analysis Center maps. The number of evaluations utilized per 10-degree longitude sector is given at the top of the figure, and at the bottom topographic features along latitude 36° N. have been sketched in. During this 6-month period there was a tendency for the air parcels to ascend as they moved eastward toward North America, reaching their highest point near the crest of the Sierra Nevada. East of the Rocky Mountains a rather strong descending motion apparently occurred on the average. Computing the mean products between adiabatically determined vertical motions and horizontal transosonde-velocity-components we find, based on 315 cases (fig. 5B), a positive correlation of 0.48 between meridional flow and vertical motion and a positive correlation of 0.17 between zonal flow and vertical motion.

Figure 5A shows the mean horizontal divergence as a function of longitude, obtained by computing the geostrophic vorticity from NAWAC maps at 12-hourly intervals along the trajectories and applying the simplified vorticity equation. During this period there are indications of horizontal convergence over and to the west of the North American continent at 300 mb., with a maximum of convergence to the east of the Rocky Mountains and a minimum of convergence just to the west of the Sierra Nevada.

5. POWER SPECTRA FOR TRANSOSONDE FLIGHTS

For each transosonde flight, the contributions of oscillations with various frequencies to the variance of the series were determined for the speed (V) and the zonal (u') and meridional (v') velocity components in the manner indicated by Tukey [4]. Also computed were the variations with frequency of the inphase-outphase relationships (cospectrum) and 90-degree phase lag relationships (quadrature spectrum) between the zonal and meridional velocity components. Figure 6 shows the average variation with frequency of these parameters for the 30 flights of at least 4 days duration. A peak in the variance as a function of frequency means that fluctuations at that frequency are more pronounced than fluctuations at adjacent frequencies, and from this it is usually assumed that there are "predominant eddies" through which the air parcels and constant level balloons are streaming. However, Gifford [2] and others believe

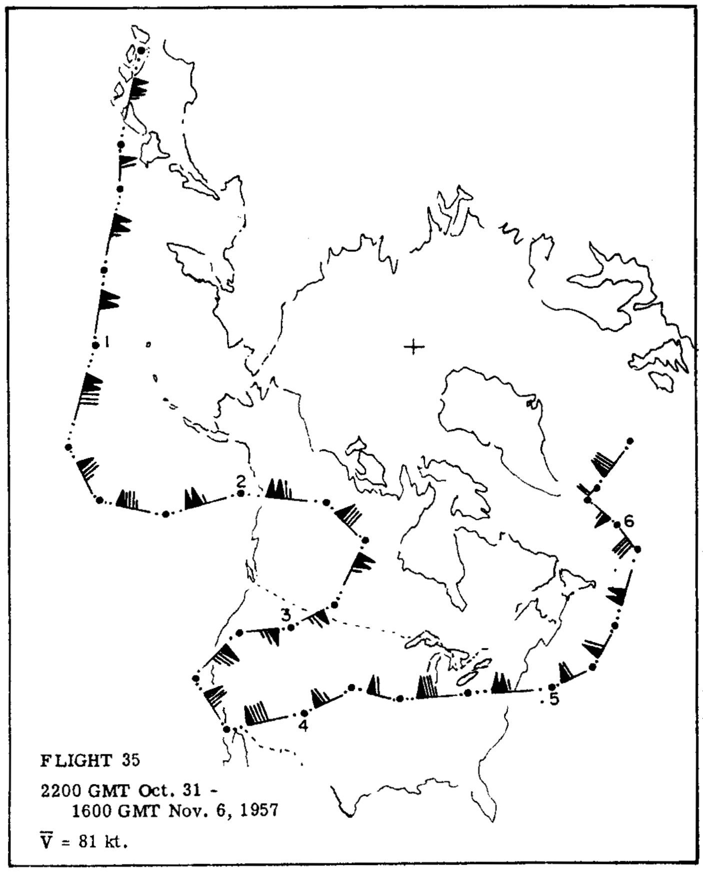

FIGURE 4.—Trajectory of Flight 35 with the 6-hour average velocities plotted at 6-hourly intervals along the path. Numbers along the trajectory indicate number of days since balloon release.

[2] Private communication.

TABLE 2.—*Monthly statistics of 12-hour average 300-mb. accelerations obtained from transosonde flights for September 1957–February 1958*

Month 1957–58	Percentage of cases in which tan. acc., $\dot{V}$, and normal acc., $(V\dot{\theta})$, exceed the given value (kt./hr.)							Average tan. acc. (kt./hr.)	Average normal acc. (kt./hr.)	Corr. coeff. between tan. and normal acc.	Corr. coeff. between tan. acc. and meridional flow	Cases
	1	2	3	4	6	8	10					
September	79 (73)	39 (52)	20 (33)	12 (21)	6 (15)	2 (7)	2 (2)	2.2	2.7	0.13	0.15	87
October	72 (80)	44 (57)	15 (36)	10 (29)	2 (14)	0 (8)	0 (6)	1.8	3.1	−.15	.29	95
November	83 (92)	51 (73)	29 (52)	16 (42)	5 (26)	1 (17)	0 (11)	2.3	4.5	.15	.11	174
December	84 (89)	53 (72)	31 (50)	19 (41)	5 (29)	1 (17)	1 (11)	2.4	4.4	.04	.02	151
January	73 (87)	51 (60)	25 (46)	18 (38)	6 (18)	1 (9)	0 (5)	2.2	3.6	−.13	−.03	148
February	95 (95)	58 (85)	42 (69)	26 (63)	10 (53)	5 (26)	0 (11)	3.0	5.7	.05	−.31	19
Mean	79 (86)	49 (65)	26 (46)	16 (37)	5 (22)	1 (13)	0 (8)	2.3	3.9	.02	.08	674
Feb. (150 mb.)	84 (79)	51 (56)	23 (37)	14 (19)	0 (5)	0 (2)	0 (0)	2.2	2.5	−.18	.08	43

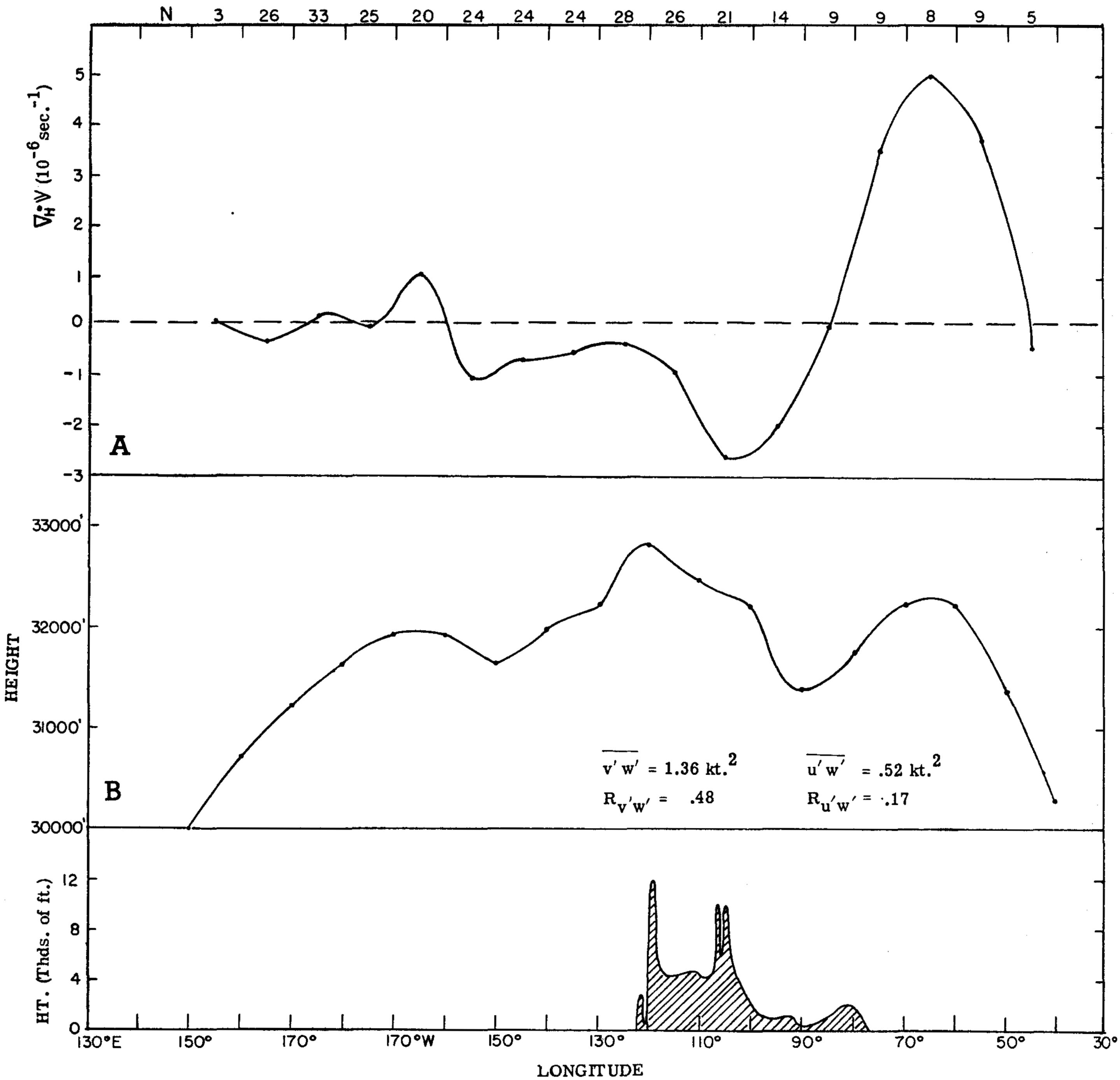

FIGURE 5.—Mean variation with longitude of horizontal divergence (A), and average elevation of air parcels initially located at the 30,000-foot positions of the balloons (B), based on transosonde flights for September 1957–February 1958. Correlation between vertical motion and zonal-meridional velocity components is inserted in B; topography along latitude 36° N. is sketched at bottom of figure; and number of evaluations per 10° longitude sector is given along the top.

that peaks in the one-dimensional spectral curves do not necessarily represent the passage of air parcels through physical cartwheel-type eddies. Bearing in mind that there is some doubt as to the interpretation and significance of one-dimensional spectral peaks, note that in figure 6A the speed and zonal components of velocity have peaks in the variance at a period near 5 days. This peak is probably the result of strong winds over Japan followed by rather strong winds off the east coast of North America, a distance the average transosonde traverses in about 5 days. The variance of the meridional wind component, however, shows a peak at a period of somewhat more than 2 days. This peak may correspond to the average time it takes a balloon or air parcel at 300 mb. to pass through a typical long wave in the westerlies. In the upper right-hand corner of

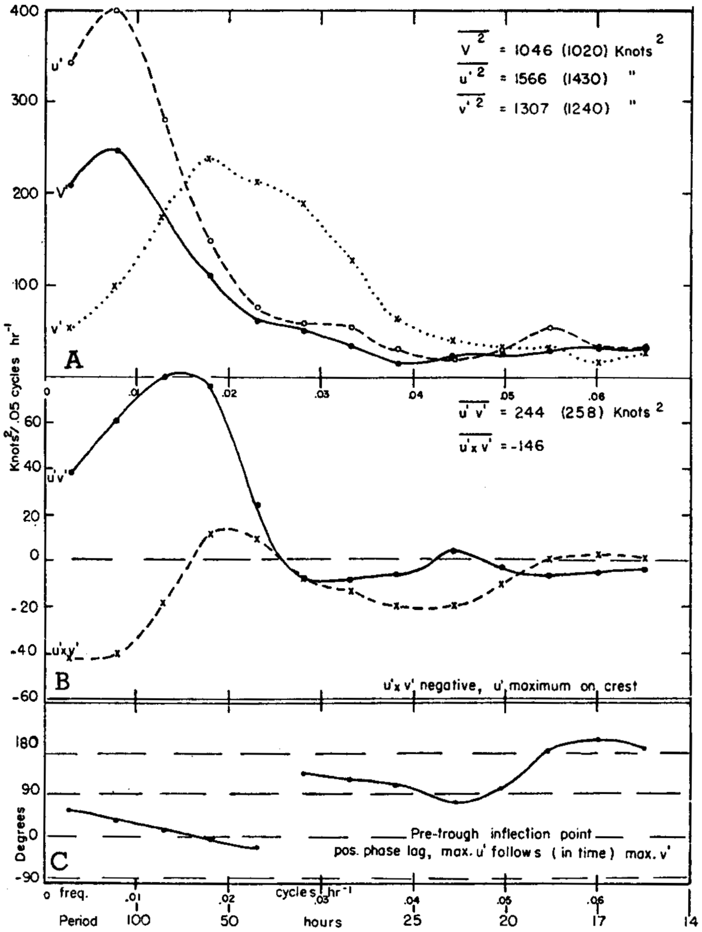

FIGURE 6.—Variation with frequency and mean values of the variance of velocity and zonal and meridional velocity components (top), the cospectrum and quadrature spectrum between zonal-meridional velocity components (middle), and the phase lag between zonal-meridional velocity components (bottom) for the 30 transosonde flights (September 1957–February 1958) of at least 4 days' duration.

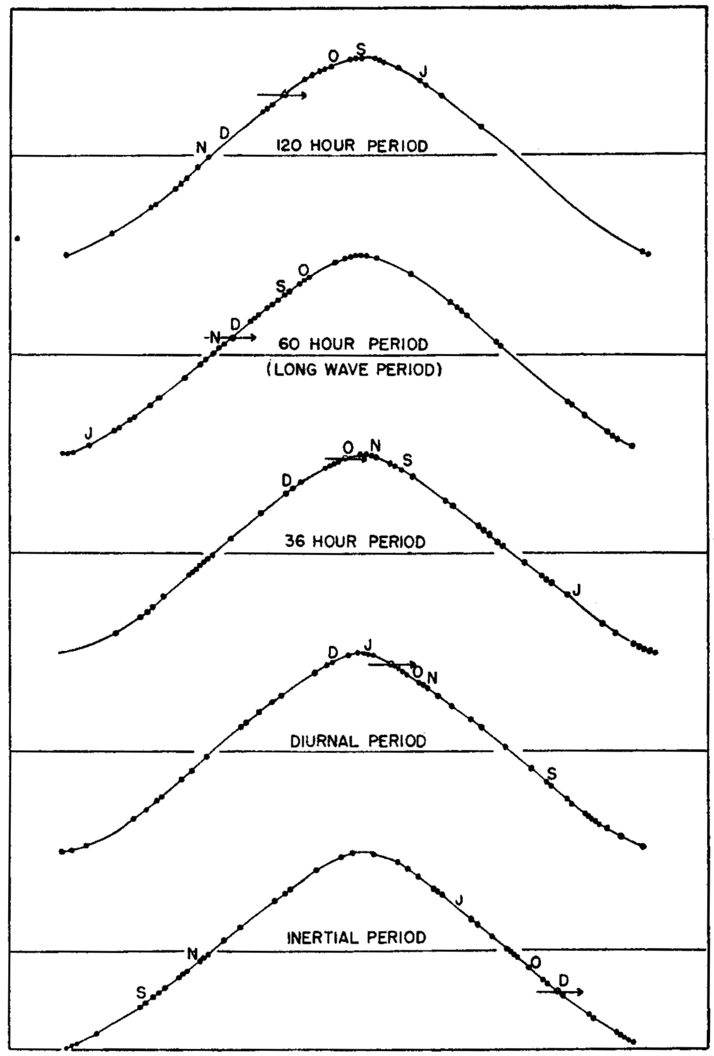

FIGURE 7.—Positions of maximum zonal wind (u') shown by dots along schematic wave-shaped trajectories of different period for all transosonde flights, September 1957–February 1958. Letters indicate mean positions of u' for the individual months, and arrows the means for all months.

figure 6A are given the average variances obtained by summing the variances per unit frequency interval, and, in parentheses, the average values obtained by summing the no-lag products obtained from individual flights. For these flights the variance of the zonal wind component was slightly greater than that of the meridional component.

The middle diagram of figure 6B shows that apparently the maximum contribution to the positive correlation between zonal and meridional velocity components (solid line) occurred for fluctuations at a period near 3 days. Most fluctuations at periods shorter than 36 hours yielded a negative correlation between these components. The quadrature spectrum (dashed line) suggests that in the mean the zonal wind component was greater on the ridges (quadrature variance negative) than in the troughs for fluctuations at all periods except those near 2 days and 17 hours.

The phase lag between zonal and meridional velocity components as a function of frequency can be obtained by finding the arctangent of the ratio of the quadrature spectrum to cospectrum, as shown in figure 6C. A phase lag of zero degrees means that the two components are exactly in phase (zonal wind component at a maximum at the pretrough inflection point) while a phase lag of 90 degrees means that the zonal wind component is at a maximum on the crest of the trajectory. We see that for fluctuations at periods of 2 days or greater the zonal wind component reached a maximum at, or slightly downstream from, the pretrough inflection point, but that for shorter period oscillations it was at the maximum somewhat downstream from the trajectory crest.

In order to make this concept somewhat clearer, in figure 7 are shown schematic wave-shaped trajectories for different periods of oscillation; namely, a 120-hour period, a 60-hour period (mean long-wave period?), a 36-hour period, a diurnal period, and an inertial period. The dots along the schematic trajectories indicate the positions of maximum zonal wind (u') for the individual flights. The letters along the trajectories indicate the mean positions of u' for the various months (S=September, etc.) and

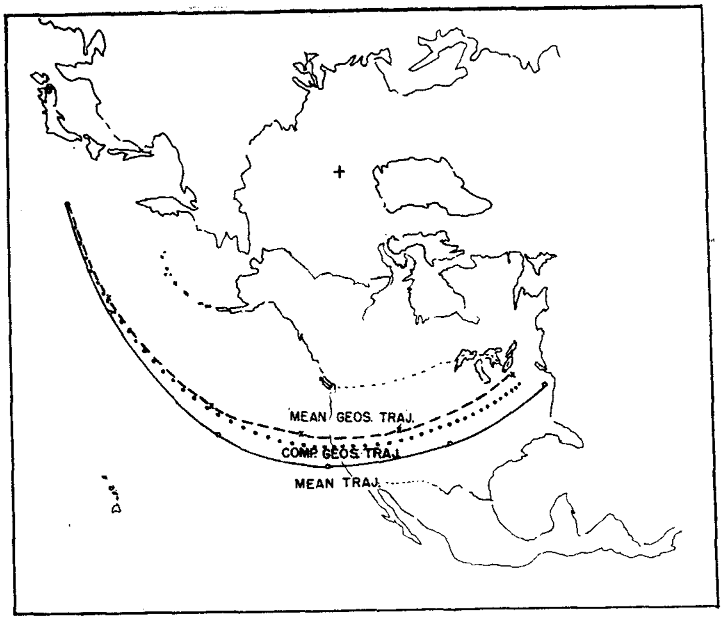

FIGURE 8.—Mean transosonde trajectory (solid line), mean geostrophic trajectory (dashed line), and mean trajectory derived from equation of motion and change in zonal wind speed with time (dotted line) for flights from September 1957–February 1958.

the arrows indicate the means for all months. It is seen that, in the case of long-period oscillations, for the great majority of flights u' reached a maximum in the pretrough southerlies, but as the periods of oscillation get smaller the positions of maximum u' become more evenly distributed or even tend to congregate in the posttrough northerlies. There is no indication of a grouping of the maximum u' values on the trajectory crest for oscillations with inertial period, as might be expected of pure inertial oscillations.

6. AGEOSTROPHIC MERIDIONAL MOTIONS DERIVED FROM TRANSOSONDE TRAJECTORIES

If the transosondes were allowed to float completely around the hemisphere, then a comparison of their mean termination latitude with the latitude of their launching point would furnish information on mean meridional ageostrophic motions. Thus, if at 30,000 feet there was a mean equatorward drift of air with a speed of 1 knot all around the hemisphere, a balloon circumnavigating the hemisphere in 10 days would find itself (assuming a steady state pressure field) 240 nautical miles south of its release point. However, since the transosondes at most circumnavigate two-thirds of the hemisphere, complications arise owing to the mean decrease of speed east of Japan (see fig. 3). Because of this decrease in speed in passing from Japan over the North American continent, ageostrophic meridional flow toward high pressure is certain to occur in this particular sector of the hemisphere. Therefore, in order to detect a hemispheric meridional drift of air, one must first subtract the above tendency. In figure 8, the solid line is the mean trajectory for all the flights, as copied from

TABLE 3.—*Mean monthly meridional ageostrophic motions determined by 3 different methods*

Month 1957–58	v_{ag} from temporal change in zonal wind and equation of motion (kt.)	v_{ag} from difference in geostrophic and actual trajectories (kt.)	v_{ag} from measurements of wind and geostrophic wind along trajectories (kt.)	Cases
September	−1.5	−10.0	−9.0	22
October	−1.9	−6.3	−1.5	45
November	−1.3	−2.7	−4.7	86
December	−.9	1.8	−1.6	83
January	−3.1	−3.0	−2.1	82
February	−5.8	1.8	5.0	12
Mean	−1.9	−2.5	−2.8	330

figure 3. The dashed line is the mean geostrophic trajectory for all the flights, obtained by constructing for all flights geostrophic trajectories originating at the transosonde positions 12 hours after their release from Japan (only front half of 300-mb. map available). The dotted line gives the geostrophic trajectory which would be estimated from knowledge of the actual trajectory and use of the zonal component of the simplified equation of motion which states that the change with time of the zonal wind speed ($\dot{u}$) equals the product of Coriolis acceleration(f) and meridional ageostrophic flow (v_{ag}). Neglected in such an equation are the effects of friction and the vertical advection of the zonal wind component. It appears from figure 8 that there is some indication of a greater ageostrophic drift of air toward the equator in this sector of the hemisphere than would be assumed from the change in zonal wind speed. The vertical advection term (from the vertical motion pattern in figure 5 and the knowledge that the zonal wind is usually increasing with height at 300 mb.) would enhance the evidence for unexplained equatorward drift to the west of the Sierra Nevada and decrease the evidence to the east, but its effect should nearly cancel out in the mean.

Because of uncertainties in the above procedure, an alternate method for estimating the deviation of meridional wind from meridional geostrophic wind was utilized. This involved simply the measurement, from 300-mb. NAWAC maps, of the meridional component of the geostrophic wind at all points where transosonde winds were available. In table 3 are shown, by month, the estimates of ageostrophic meridional wind (v_{ag}) obtained by the three techniques. The measurements of the geostrophic winds along the trajectories confirm, in the mean, the evidence for ageostrophic equatorward drift of air at 300 mb. which is not accounted for by decrease in zonal wind speed. However, it is also apparent from the table that it is the fall months that bring about this mean result; if only the winter months are used, they indicate a slight unexplained poleward ageostrophic drift of air at midlatitudes. It is hoped that the study of further transosonde flights will clarify the situation; nevertheless, it is possible that the techniques proposed here are not sufficiently reliable for the purpose at hand.

TABLE 4.—*Mean angles of indraft (i) and mean ageostrophic wind speeds* ($V-V_g$) *obtained from comparison of 300-mb. NAWAC analysis and transosonde velocities, September–November, 1957*

	Pacific Ocean area	North America
i .... degrees	−2.6	−1.1
$\|i\|$ .... do	12.6	13.3
$V-V_g$ .... knots	9.0	5.1
$\|V-V_g\|$ .... do	21.4	20.3
Cases	107	61

7. COMPARISON OF TRANSOSONDE AND GEOSTROPHIC VELOCITIES

A comparison of transosonde velocities and geostrophic velocities obtained from 300-mb. NAWAC maps shows that, despite the lack of conventional upper-air data over the Pacific, the routine 300-mb. map analysis is reasonably accurate. Table 4 gives the algebraic and absolute values of the angle between wind and geostrophic wind (i) and the difference in speed and geostrophic speed ($V-V_g$) over the Pacific and over the United States obtained from comparisons of 6-hour average transosonde velocities and geostrophic velocities. The comparison was limited to the months of September, October, and November, since in December the transosonde positions began to be plotted and utilized as analysis aids on the 300-mb. NAWAC maps. It is noted from the table that the average absolute angle between the transosonde wind and geostrophic wind over the Pacific was only 12.6 degrees, about the same as over the United States. The average algebraic value of i over the Pacific was −2.6 degrees (flow toward high pressure), in agreement with the decrease in wind speed between Japan and North America. The transosonde winds, however, averaged about 9 knots greater than the geostrophic winds over the Pacific while over North America the difference was only 5 knots, this despite the fact that on the average balloons were flying at 280 mb. over North America and at 290 mb. over the Pacific. It is believed that this 9-knot difference is significant and is due to the tendency to linearize contour spacing over the Pacific and thus underestimate the wind strength near the jet cores where the majority of the balloons fly. The general accuracy of the Pacific analysis in regions of little data may be due to the relative smoothness of the 300-mb. flow east of Japan and the scarcity of small-scale oscillations—oscillations which could pass undetected through the sparse observational network.

8. CONCLUSION

In conclusion, these routine transosonde flights offer a wealth of material for research, and can be of considerable use in weather analysis and forecasting, particularly in the forecasting of jet-stream conditions for high-flying aircraft. However, beginning in September 1958, the transosonde flights will take place at 150 mb., forced to this higher elevation by commercial jet aircraft. It remains to be seen whether transosonde observations at this new level are of the same utility as the flights at 300 mb.

ACKNOWLEDGMENT

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